TU Delft

Delft University of Technology

Water stress detection in the Amazon using radar

van Emmerik, Tim; Steele-Dunne, Susan; Paget, Aaron; Oliveira, Rafael S.; Bittencourt, Paulo R.L.; Barros, Fernanda de V.; van de Giesen, Nick

DOI
10.1002/2017GL073747

Publication date
2017

Document Version
Final published version

Published in
Geophysical Research Letters

Citation (APA)
van Emmerik, T., Steele-Dunne, S., Paget, A., Oliveira, R. S., Bittencourt, P. R. L., Barros, F. D. V., & van de Giesen, N. (2017). Water stress detection in the Amazon using radar. *Geophysical Research Letters*, *44*(13), 6841-6849. https://doi.org/10.1002/2017GL073747

Important note
To cite this publication, please use the final published version (if applicable).
Please check the document version above.

Copyright
Other than for strictly personal use, it is not permitted to download, forward or distribute the text or part of it, without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license such as Creative Commons.

Takedown policy
Please contact us and provide details if you believe this document breaches copyrights.
We will remove access to the work immediately and investigate your claim.

This work is downloaded from Delft University of Technology.
For technical reasons the number of authors shown on this cover page is limited to a maximum of 10.

AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER
10.1002/2017GL073747

Key Points:
- Simultaneous ground measurements of tree water status and RapidScat backscatter
- Diurnal variation in backscatter differs during wet and dry seasons
- Radar backscatter is sensitive to tree water stress in Amazon

Supporting Information:
- Supporting Information S1

Correspondence to:
T. van Emmerik,
t.h.m.vanemmerik@tudelft.nl

Citation:
van Emmerik, T., S. Steele-Dunne, A. Paget, R. S. Oliveira, P. R. L. Bittencourt, F. de V. Barros, and N. van de Giesen (2017), Water stress detection in the Amazon using radar, *Geophys. Res. Lett.*, *44*, 6841–6849, doi:10.1002/2017GL073747.

Received 6 APR 2017
Accepted 1 JUL 2017
Accepted article online 6 JUL 2017
Published online 13 JUL 2017

©2017. American Geophysical Union. All Rights Reserved.

Water stress detection in the Amazon using radar

Tim van Emmerik[1], Susan Steele-Dunne[1], Aaron Paget[2], Rafael S. Oliveira[3], Paulo R. L. Bittencourt[3], Fernanda de V. Barros[3], and Nick van de Giesen[1]

[1]Water Resources Section, Delft University of Technology, Delft, Netherlands, [2]Department of Marine Sciences, University of Connecticut, Groton, Connecticut, USA, [3]Department of Plant Biology, Institute of Biology, UNICAMP, Campinas, SP, Brazil

Abstract The Amazon rainforest plays an important role in the global water and carbon cycle, and though it is predicted to continue drying in the future, the effect of drought remains uncertain. Developments in remote sensing missions now facilitate large-scale observations. The RapidScat scatterometer (K_u band) mounted on the International Space Station observes the Earth in a non-Sun-synchronous orbit, which allows for studying changes in the diurnal cycle of radar backscatter over the Amazon. Diurnal cycles in backscatter are significantly affected by the state of the canopy, especially during periods of increased water stress. We use RapidScat backscatter time series and water deficit measurements from dendrometers in 20 trees during a 9 month period to relate variations in backscatter to increased tree water deficit. Morning radar bacskcatter dropped significantly with increased tree water deficit measured with dendrometers. This provides unique observational evidence that demonstrates the sensitivity of radar backscatter to vegetation water stress, highlighting the potential of drought detection and monitoring using radar.

1. Introduction

The Amazon, which contains half of the world's rainforests, plays a key role in the global water and carbon budget [*Saatchi et al.*, 2007; *Binks et al.*, 2016]. However, the Amazon still remains a poorly understood component of the global carbon and water cycle [*Samanta et al.*, 2010]. The Amazon is predicted to continue drying in the future, which might accelerate climate change through carbon losses and change surface energy balances [*Cox et al.*, 2008]. For example, the extensively studied 2005 drought reversed the Amazon from a long-term carbon sink into a carbon source. Amazon forests appear to be vulnerable to increasing moisture stress, and future droughts have the potential to considerably change the water and carbon balance [*Phillips et al.*, 2009]. Models and observations do not all agree on the effect of drought on the Amazon. The current debate on whether or not the Amazon greens up during the dry season underscores the need for greater understanding of the effect of drought on the Amazon (*Huete et al.* [2006] and *Saleska et al.* [2007] versus *Samanta et al.* [2010] and *Morton et al.* [2014]). Furthermore, understanding drought effects and the Amazon's resilience to drought is critical to understand their impact on the carbon and water cycles [*Hilker et al.*, 2014].

With an increase in episodic droughts, there is a need for spaceborne observations, in addition to field and modeling studies [*Asner and Alencar*, 2010; *van Emmerik et al.*, 2017b]. New satellite observations provide opportunities for better detection and understanding of drought [*AghaKouchak et al.*, 2015]. Recent research suggests that radar observations might yield valuable insight into canopy water status. Several studies have identified diurnal variations in backscatter over the Amazon [*Birrer et al.*, 1982; *Satake and Hanado*, 2004; *Frolking et al.*, 2011; *Jaruwatanadilok and Stiles*, 2014; *Paget et al.*, 2016] and other vegetated areas [*Friesen*, 2008; *Friesen et al.*, 2012; *Konings et al.*, 2017]. Radar is sensitive to vegetation because of direct backscatter from the canopy and attenuation of the signal as it travels through the vegetation layer [*Ulaby et al.*, 1982]. Both are influenced by the leaf area in the vegetation layer and the vegetation dielectric properties. The latter are in turn a function of vegetation water content. The leaf area is mainly a function of tree phenology, governed by leaf flush and leaf fall. The number of leaves is mainly a function of tree phenology, governed by leaf flush and leaf fall. During periods of low soil moisture availability, backscatter is mainly sensitive to vegetation water content [*Steele-Dunne et al.*, 2012; *van Emmerik et al.*, 2015a], through the dielectric response of the vegetation to water stress [*van Emmerik et al.*, 2015b, 2017a].

Diurnal differences in backscatter might be the key for water stress detection using radar. *Birrer et al.* [1982] found that backscatter over the Amazon rainforest at sunrise was 0.5–1 dB higher than during the rest of the day. *Satake and Hanado* [2004] also found diurnal variation in backscatter and suggested that these were caused by changes in either vegetation water content or dew. *Frolking et al.* [2011] used QuikSCAT backscatter, in combination with a Tropical Rainfall Measuring Mission precipitation-derived measure of water deficit, to hypothesize that the dry season reduction in backscatter is due to water stress-induced changes in canopy water status. Strong negative anomalies in predawn backscatter were found during the 2005 drought. Measured tree mortality rates during this period [*Phillips et al.*, 2009] suggested that these anomalies were caused by changes in tree water status, rather than dew. *Jaruwatanadilok and Stiles* [2014] used 10 years of QuikSCAT data and found a consistent difference between ascending and descending overpasses over tropical forests and suggested that this is very likely due to differences in vegetation moisture content. *Friesen* [2008] used simple regional vegetation modeling to demonstrate that the diurnal variation in ERS C band backscatter coincided with the onset of water stress over West Africa. The largest differences were found at the start of the dry season, ruling out interception, dew, or top soil moisture dynamics, and leaving vegetation water content as the most plausible explanation for diurnal differences. To test this hypothesis, *Steele-Dunne et al.* [2012] modeled L and C band backscatter over a forest canopy and demonstrated that during periods of low soil moisture availability, backscatter is mainly sensitive to changes in vegetation water content. Recent work by *Paget et al.* [2016] and *Konings et al.* [2017] used RapidScat backscatter to confirm that the theorized diurnal cycle over tropical forests definitely exists. In situ data in combination with backscatter is required to test the hypothesis that vegetation water content is the primary driver of water stress-related diurnal variation in backscatter. This paper presents a first study that uses field data of tree water status in combination with K_u band radar backscatter to confirm that changes in vegetation water content associated with water stress are apparent in backscatter.

Data from the RapidScat scatterometer [*Cooley*, 2013] on board the International Space Station (ISS) offer a unique opportunity to investigate diurnal variations in backscatter with spaceborne radar. Due to the orbit of the ISS, the daily ascending and descending overpass times shift and eventually cover a complete diurnal cycle. These unique orbit characteristics allow us to study changes in backscatter for specific hours of the day. A diurnal cycle for backscatter can be constructed each month, allowing us to study how the diurnal cycle changes in time and to confirm the hypothesis of *Friesen et al.* [2012], *Steele-Dunne et al.* [2012], and *van Emmerik et al.* [2015a] that diurnal variations in backscatter are related to water stress. Here we compare backscatter data from RapidScat to dendrometer data from 20 trees in the Amazon rain forest from July 2015 to April 2016. Diurnal cycles of horizontally (HH) and vertically (VV) copolarized backscatter are determined for each month. First, these are compared to the water deficit calculated from the dendrometer data to investigate how the diurnal cycle of backscatter changes in the transition from the wet to dry season. Second, the temporal variation in predawn backscatter will be compared to the water status of the measured trees to confirm the hypothesis that increasing water stress leads to a decrease in predawn vegetation water content and backscatter.

2. Methods

2.1. Study Area

For this study we use ground data obtained at a research station in the Amazon rainforest (2.6085°S, 299.8107°W), 60 km northwest of Manaus, Brazil. The study area is characterized by a tropical climate with an average dry season from June to October. During the measurement period, there was about 12 h of daylight, roughly between 6 A.M. and 6 P.M. local time. A land cover map of the study area is presented in the supporting information section S1, including the location of the measurement site and the footprint of the radar data used. The land cover classification was retrieved from the European Space Agency Climate Change Initiative land cover map [*European Space Agency*, 2016]. Radar data from July 2015 to August 2016 and ground measurements from August 2015 to April 2016 were available.

2.2. Radar Data

RapidScat, launched in September 2014, is a rotating pencil-beam scatterometer installed on the International Space Station (ISS). Scatterometers are a type of active microwave remote sensing, which emits microwave energy toward the Earth's surface and measures the reflected energy. RapidScat measures both horizontally (HH) and vertically polarized (VV) K_u band (13.6 GHz) backscatter. The incidence angle various between

44–54° (HH) and 51–61° (VV), and the resolution for the normalized backscatter is 26 × 37 km. The ISS, and therefore RapidScat, has a non-Sun-synchronous orbit, which allows for different local time of day observations as the orbit progresses [*Paget et al.*, 2016]. Every day the overpass time shifts to an earlier time of the diurnal cycle by around 30 min, meaning that a complete diurnal cycle for each overpass mode is covered after 2 months. Combining ascending and descending data will cover a diurnal cycle every single month. For more details on the sensor and initial data processing see *Paget et al.* [2016] and *Madsen and Long* [2016]. For this study we use HH and VV polarized backscatter (L1B v1.2 from NASA Jet Propulsion Laboratory) from July to August 2016 that was retrieved over the Amazon between 1.6–3.6°S and 298.8–300.8°W.

The backscatter from the 2° × 2° area was resampled into 25 subareas of 0.4° by 0.4°, which was chosen as a compromise to maximize the number of data per subarea, but minimizing spatial information loss. For this study we only use backscatter that has its entire footprint within 1° longitude and latitude from the measurement location. We applied a land cover-based mask to filter out the observations influenced by urban areas, water bodies, and flooded forests (see supporting information section S1). Finally, the spatially filtered backscattered was averaged for each time step, arriving at the final backscatter time series for both HH and VV.

We found that depending on the hour of the day, the spatial variability in backscatter can vary over the forest canopy. Therefore, in the following analyses data retrieved at 5 and 6 A.M. and 5 and 6 P.M. were used for morning and evening data, respectively. At other times, the standard deviation of the spatially averaged backscatter increases from 0.7 dB to 1.1 dB at noon; see supporting information section S3.

Combining ascending and descending overpass data, diurnal cycles of radar backscatter were constructed for every month. For the measurement period of July 2015 to August 2016 this resulted in 14 diurnal cycles. From these diurnal cycles we also extracted backscatter for specific hours of the day. For this analysis, data at 5 and 6 A.M./5 and 6 P.M. were used, which yield a time series of morning and evening backscatter at these specific times. We also computed the diurnal variation $\Delta\sigma_t^0$ by subtracting the evening backscatter from the morning backscatter:

$$\Delta\sigma_t^0 = \sigma_{t,\mathrm{AM}}^0 - \sigma_{t,\mathrm{PM}}^0 \tag{1}$$

with chosen time of day t.

2.3. Ground Data

A total of 20 individual trees were measured during this experiment, covering 7 tree species, with a broad range of average height and wood density. An overview of the trees measured can be found in the supporting information section S2. Data from August 2015 to April 2016 were used.

Dendrometers (ZN12-T-2IP, Natkon.ch, Switzerland) were installed at 1.5 m above ground level. Two potentiometers measured the thickness of the bark and the xylem every 10 min. Changes in thickness are measured by the compression or relaxation of the spring of the potentiometers.

Over long periods it can be difficult to separate the water-induced stem radius change from growth-induced radius change [*Zweifel and Häsler*, 2001]. Bark time series were detrended for growth in order to use it as a direct measure of drought stress in trees. For this, the growth line of the species was determined, based on the local maximum values of stem radius [*Zweifel et al.*, 2005; *Ehrenberger et al.*, 2012].

For this method, it is assumed that the local maximum of the stem radius does not decrease over time. A linear relation is then assumed between the local maximum values, which represents the growth line. Any deviation is the actual deficit. The actual water deficit was calculated by subtracting the measured changes in stem radius from the growth line.

$$\Delta W = D_{b,\mathrm{pot}} - D_{b,\mathrm{act}} \tag{2}$$

with total water deficit ΔW, growth line $D_{b,\mathrm{pot}}$, and change in bark thickness $D_{b,\mathrm{act}}$. An example can be found in supporting information section S4.

To compare the dendrometer data with radar backscatter, the water deficit time series was resampled at the same time of day as the backscatter data used (5–6 A.M./5–6 P.M.), yielding daily morning and evening values. Subsequently, these were subtracted to calculate the daily diurnal difference. We use the Spearman rank coefficient to evaluate the significance of the relationship between water deficit and backscatter. We also looked at the changes in xylem thickness, as this is a good indicator of tree water status and water use,

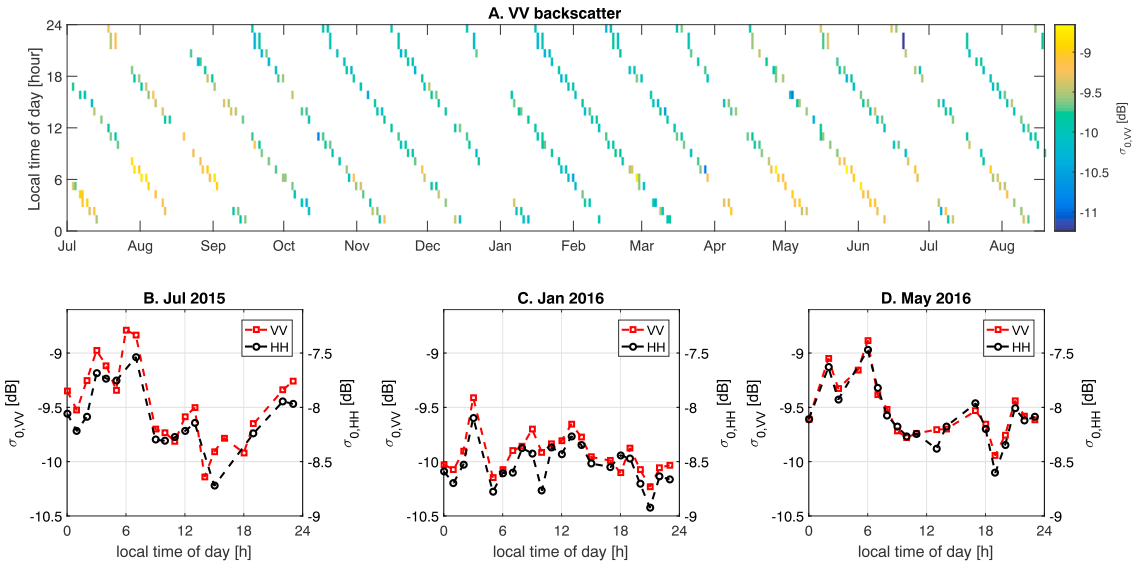

Figure 1. (a) Backscatter per hour of the day for VV polarized backscatter from July 2015 to August 2016 and diurnal cycles of VV and HH backscatter in (b) July 2015 (wet period), (c) January 2016 (dry period), and (d) May 2016 (wet period).

transpiration rate, and leaf water status [*Perämäki et al.*, 2005; *Sevanto et al.*, 2008]. Also, this is not affected by absorption and evaporation of water from the bark tissue [*Sevanto et al.*, 2011]. Wet conditions result in an increase in the xylem diameter, and drought leads to a decrease. The exact relationship between xylem thickness and sap flow varies with species and over time.

3. Results

3.1. Backscatter Time Series and Diurnal Cycles

Figure 1a presents the average backscatter over the study area from July 2015 to April 2016. Here it can be seen how the non-Sun-synchronous orbit affects the data availability. After 2 months, a full diurnal cycle is covered. Three clear periods can be distinguished. From July to October 2015 the backscatter in the morning was higher than in the evening. From October 2015 to April 2016 the diurnal variation decreased, and backscatter is quite stable during the day. From April onward, the morning backscatter increases again. For the periods with a considerable difference between morning and evening backscatter, the difference can reach up to 1.2 dB for both VV and HH (see supporting information section S5).

Figures 1b–1d present diurnal cycles for these three distinct periods. In July 2015 (Figure 1b), the maximum backscatter was around 6 A.M., after which it decreased during the day. In January, 2016 (Figure 1c) the morning backscatter had decreased and the diurnal variation is low. In May 2016, the diurnal variation increased again (Figure 1d), with again the maximum backscatter around 6 A.M. The diurnal variation in backscatter was similar to the expected variation in vegetation water content in the canopy. Right before sunrise, when photosynthetic activity was low, the water content was at its daily maximum. With increasing net solar radiation, the vegetation loses water through transpiration, decreasing to a minimum in the evening (Figures 1b and 2d). At night vegetation replenishes its water storage again. However, during dry periods (Figure 1c) there might not be sufficient water available in the soil, leading to decreasing maximum water content. Eventually, the diurnal variation will also decrease [*Slayter*, 1967]. All monthly diurnal cycles are presented in supporting information section S6.

3.2. Predawn Time Series

The plant water deficit, xylem thickness, and VV and HH backscatter are presented in Figures 2a–2c. For the water deficit and xylem thickness, three individual trees, and the mean values of all trees are shown. The individual trees were selected to illustrate the range of values across species. Water deficit and xylem thickness of all trees is shown in Figure S7 in the supporting information. The periods from July 2015 to April 2016 can be separated in three phases. In the first phase, water deficit was low, the xylem thickness was stable, and backscatter was high. In September 2015, water deficit started to increase. At the same time, the xylem

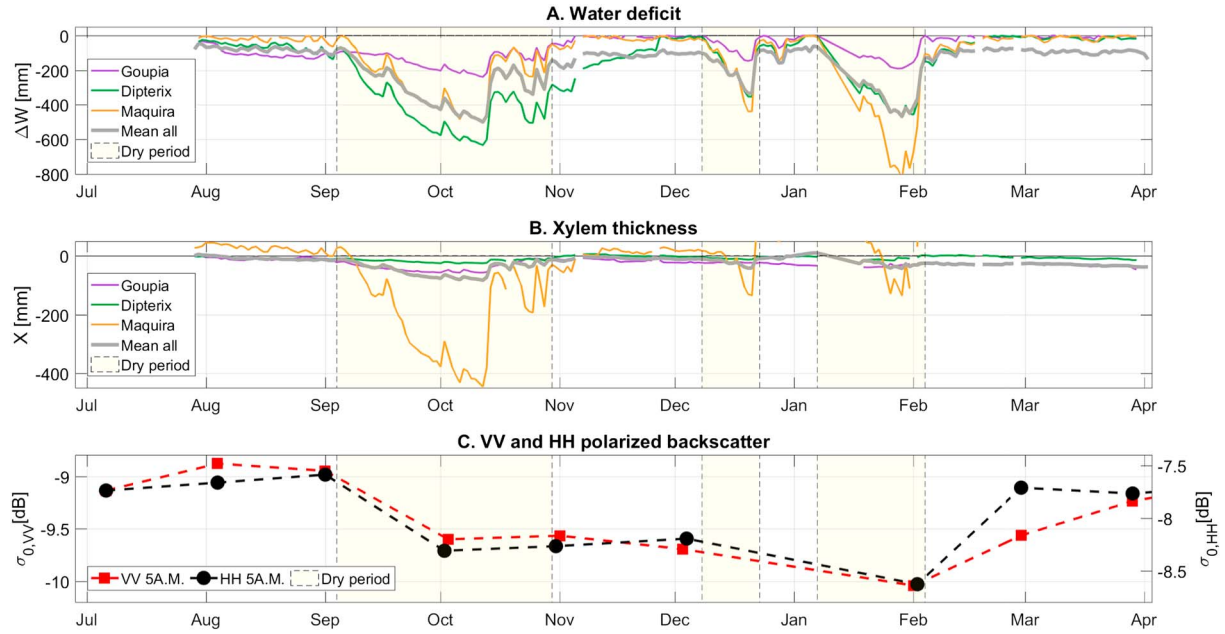

Figure 2. (a) Water deficit and (b) Xylem thickness for *Goupia glabra*, *Dipterix odorata*, and *Maquira sclerophylla* trees and mean of all trees, and (c) VV and HH polarized 5 A.M. backscatter, from July 2015 to August 2016. The periods of increased water deficit are indicated with the yellow background.

thickness also decreased, indicating lower transpiration rates and lower water content in plant tissues. Backscatter for both VV and HH also dropped significantly from −9 to −9.6 dB (VV) and from −7.5 to −8.4 dB (HH). From October 2015 to February 2016, a second phase of increased water deficit can be distinguished. Backscatter during this period did not show much variability, even though the water deficit recovers in November and December 2015. Xylem thickness in the *Goupia glabra* was still lower, which suggests that the leaf water content might not have recovered. The water deficit was determined using the bark thickness, which is a measure of the total water content in the tree. However, a decreasing water deficit in the trunk might not have resulted yet in recovery of leaf water content. As RapidScat measured at high frequency (13.4 GHz), backscatter was mainly sensitive to changes in leaf water content [*Ulaby et al.*, 1984; *van Emmerik et al.*, 2015a]. Therefore, the recovery might not have been as clear in the backscatter signal. The moment water deficit increased to a maximum in February 2016, backscatter again dropped with 0.5 dB. After February 2016, water deficit went back to zero for all three trees, suggesting recovery of the vegetation. Also backscatter increased from −10 to −9.2 dB (VV) and from −8.7 to −7.7 dB (HH) between February and April 2016. In this phase, the plant water content recovered more than after the first dry period (September–November 2015). Also, during this period leaf flush might have occurred. Although water deficit was low, it takes some time before leaf development results in biomass increase. This would explain the delayed increase in backscatter.

During the peaks in water deficit in October 2015 and February 2016, both HH and VV backscatter significantly dropped by 0.5 to 0.9 dB. The effect of water stress is not only visible in the morning values. Figure 3 presents morning and evening VV (Figures 3a and 3b), HH (Figures 3d and 3e) backscatter values and the diurnal variation for both VV (Figure 3c) and HH (Figure 3f), and water deficit during morning (Figure 3g), evening (Figure 3h), and its diurnal variation (Figure 3i). In addition to the predawn measurements, the evening values clearly dropped around 0.5 dB for both VV and HH. Also, the diurnal variation decreased from 1 to 0 dB during the peaks in water deficit. Ground measurements on the trees give a measure of water stress, which was largest in October 2015 and February 2016. In these months, morning backscatter, evening backscatter, and the diurnal variation in backscatter significantly dropped.

From Figures 2 and 3 it can be seen that the drop (and increase) in backscatter during the wet to dry (and dry to wet) period is significant (0.7–1.0 dB). These two transition phases will be discussed separately, to investigate the sensitivity of backscatter to changing water status in the canopy. Figure 4 presents the relationship between measured water deficit of four tree species during (1) the transition from wet to dry, from August to November 2015 (Figures 4a–4d), and (2) the transition from dry to wet, from February to April 2016 (Figures 4e–4h). For the first transition, water deficit was strongly related to backscatter. The water deficit was

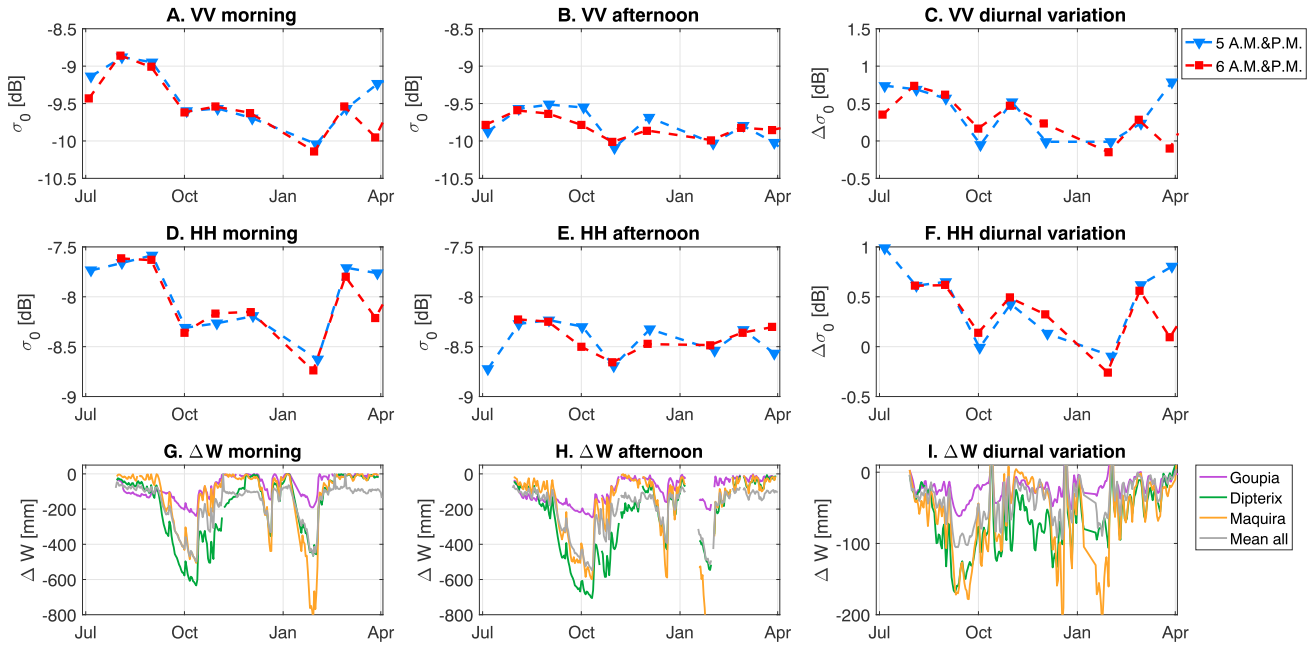

Figure 3. VV backscatter time series for (a) 5 and 6 A.M., (b) 5 and 6 P.M., and (c) diurnal difference at 5 A.M./5 P.M. and 6 A.M./6 P.M., HH backscatter time series for (d) 5 and 6 A.M., (e) 5 and 6 P.M., and (f) diurnal difference at 5 A.M./5 P.M. and 6 A.M./6 P.M., water deficit time series for (g) 5 A.M., (h) 5 P.M., and diurnal difference at (i) 5 A.M./5 P.M.

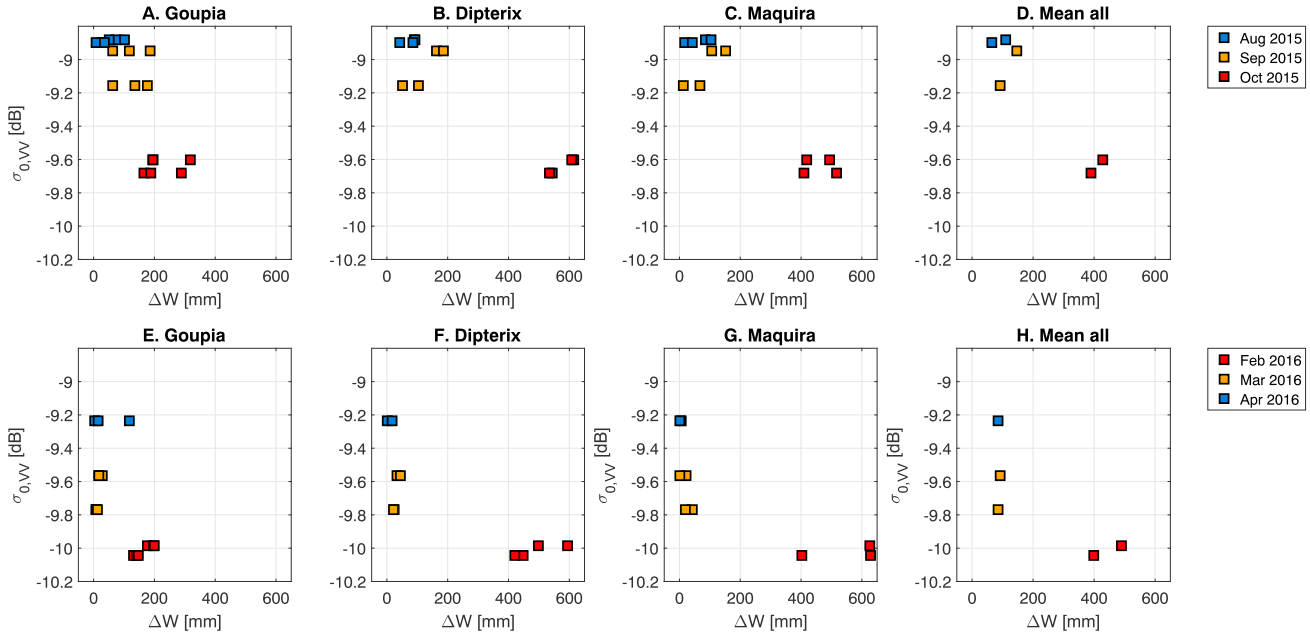

Figure 4. Water deficit ΔW and backscatter σ_0 for three tree species and mean water deficit of all trees at 5 A.M. and 6 A.M. Each marker type corresponds to an individual (circle, triangle, or square), and the color refers to the time of measurement ((a–d) August to October 2015. (e–h) February to April 2016). Three *Goupia glabra* individuals (Figure 4a/4e), two *Dipterix odorata* individuals (Figure 4b/4f), two *Maquira sclerophylla* individuals (Figure 4c/4g), and mean water deficit using all trees (Figure 4d/4h). Note that the *y* axis values are the same across all columns.

different in magnitude for all tree species. Water deficit is influenced by tree size and stress coping mechanisms. In general, the different individuals react similarly, also compared to the mean water deficit using data from all trees (Figure 4d/4h). From Figures 4a–4d it is clear, however, that although the variability in water deficit varies between species, the canopy as a whole significantly affects backscatter. Using the Spearman rank test, it was found that the relation between lower backscatter and increased water deficit is statistically significant. Confidence boundaries ranged from 0.9 for water deficit of individual trees to 0.99 for mean water deficit. For the second transition, from dry to wet, again, a clear correlation can be seen. However, though the dendrometer data indicate a reduction in water stress by March, the backscatter continues to increase in April. This suggests that there may be a delay between recovery in the trunk and the leaves, which could be associated with leaf development after the decrease of water deficit (leaf flushing).

4. Discussion

The most significant sign of vegetation water stress was the change in morning backscatter. During periods with the highest water deficit across the measured trees, VV and HH backscatter were lowest. This is in line with previous studies that associated anomalies in morning backscatter to drought effects in the canopy, such as *Saatchi et al.* [2013] and *Frolking et al.* [2011]. The ground measurements provide the first observational evidence of the effect of vegetation water stress on radar backscatter.

During periods of increased water deficit, based on in situ tree measurements, the diurnal variation decreased. This was attributed to decrease in morning backscatter, which can be explained by the decrease in canopy moisture content. The inability to refill completely during the night is one of the signs of vegetation water stress [*Hsiao and Acevedo*, 1974]. For the first time, changes in diurnal backscatter cycle were linked to changes in vegetation water status based on ground measurements. This allows studying subseasonal variations, such as the observed transitioning from wet to dry conditions. Vegetation dynamics change on a significantly shorter time scale, and the diurnal backscatter cycles obtained on a shorter timescale gave additional insight in the effect of water stress on vegetation.

A difference was observed between the transition from wet to dry and the transition from dry to wet. Water deficit has an immediate effect on leaves [*Slayter*, 1967; *Tardieu and Davies*, 1993], and this is observed as a drop in backscatter. There is a delay between increase in xylem thickness and leaf development/recovery after the dry period [*Sevanto et al.*, 2002]. Results show that backscatter continues to increase after xylem has recovered, suggesting leaf development or recovery after the transition from dry to wet period. Leaf flushing is likely to occur when water deficit is low. After leaf flushing, new leaves need time to develop and gain biomass [*Asner and Alencar*, 2010; *Samanta et al.*, 2012], which causes a delay in the backscatter response. Besides variation in canopy water content, changes in leaf area can have a considerable impact on backscatter. The drop in backscatter as observed between September and October 2015 coincides with a steep increase in water deficit. During periods of decreased water deficit, canopy water content decreases first. Eventually, sustaining water deficit will lead to leaf fall, decreasing the leaf area. Decreased leaf area could be an explanation for the delay in recovery in November 2015 and February 2016. Although water deficit decreases to almost zero, the recovery is not directly observed in the backscatter. After November 2015 no increase is observed at all, and after February 2016 an increase in backscatter is observed after 1 month. When water deficit is decreased, the leaf area does not immediately increase as trees need time to gain biomass and develop new leaves. In November 2015, the recovery was not sufficient to allow for increase in leaf area. After February 2016, biomass gain did result in increased leaf area. In situ observations of leaf area are not available for this study period. However, this seasonal pattern corresponds to observations from earlier years at the same measurement site [*Pontes Lopes et al.*, 2016]. For 2012 and 2013, leaf flush occurred 1 to 2 months after the transition to the wet season, with increased precipitation and lower tree water deficit.

This paper demonstrates the value of coincident backscatter and field measurements of tree water status. The trees measured during this fieldwork had a temporally similar response. In other canopies this might not be the case. Additional research is essential to understand and quantify if the backscatter time series over a less temporally similar canopy also contains a clear stress signature. For this study, only 9 months of data were available. Future work might not only extend the length of the data series to incidental dry periods but also investigate seasonality, phenology, and monthly anomalies. This will give more insight in how to quantify the effect of vegetation water stress.

5. Conclusions

Simultaneous ground measurements and RapidScat K_u band radar backscatter were used to relate variation in backscatter to increased tree water deficit. During two dry periods, increased vegetation water stress resulted in drops in radar backscatter.

Predawn backscatter showed the largest sensitivity to increased vegetation water stress. Both VV and HH backscatter dropped 0.5 to 1 dB as a result of increased tree water deficit. Also, evening VV and HH backscatter and the diurnal variation in radar backscatter dropped considerably during periods of vegetation water stress. This clearly demonstrates the strong relation between water status of the canopy and radar backscatter.

Changes in the diurnal cycle of backscatter were found, associated with the change in water status of the vegetation canopy. During the wet period, morning backscatter was up to 1 dB higher than in the evening. During the dry period the diurnal variation in backscatter decreased to nearly zero.

RapidScat backscatter is mainly sensitive to changes in leaf water content. The largest variation in backscatter was observed during the transition phases from a wet period to a dry period and vice versa. At the start of the first dry period, increased water deficit in the canopy resulted in an immediate drop in backscatter. During the wetting phase, backscatter followed, although with a delay, the recovery of the vegetation. During recovery, the trunk recovers faster than the leaves.

Drought detection and monitoring in tropical forests is a major challenge. This paper found that radar backscatter is sensitive to increased water deficit in the Amazon, which demonstrates the value of drought monitoring and detection using radar remote sensing.

Acknowledgments
The work of S.C. Steele-Dunne was supported by a Vidi grant 14126 from the Dutch Technology Foundation STW, which is part of the Netherlands Organisation for Scientific Research (NWO) and which is partly funded by the Ministry of Economic Affairs. We thank FAPESP GOAmazon project 2013/50431-2 in whose field campaign data were collected. We thank the Large-Scale Biosphere-Atmosphere (LBA) Program at the National Institute for Amazon Research (INPA) for logistical and infrastructure support during field measurements. The authors are very grateful to Pierre Gentine and Laura Borma. RapidScat data can be obtained freely at ftp://podaac-ftp.jpl.nasa.gov/. Dendrometer data may be obtained from Fernanda de V. Barros (e-mail: nandavascon@gmail.com). Accelerometer data may be obtained from Tim van Emmerik (e-mail: t.h.m.vanemmerik@tudelft.nl).

References

AghaKouchak, A., A. Farahmand, F. Melton, J. Teixeira, M. Anderson, B. Wardlow, and C. Hain (2015), Remote sensing of drought: Progress, challenges and opportunities, *Rev. Geophys.*, *53*, 452–480, doi:10.1002/2014RG000456.

Asner, G. P., and A. Alencar (2010), Drought impacts on the Amazon forest: The remote sensing perspective, *New Phytol.*, *187*(3), 569–578.

Binks, O., P. Meir, L. Rowland, A. C. L. Costa, S. S. Vasconcelos, A. A. R. Oliveira, L. Ferreira, B. Christoffersen, A. Nardini, and M. Mencuccini (2016), Plasticity in leaf-level water relations of tropical rainforest trees in response to experimental drought, *New Phytol.*, *211*(2), 477–488.

Birrer, I., E. Bracalente, G. Dome, J. Sweet, and G. Berthold (1982), σ signature of the Amazon rain forest obtained from the SeaSat scatterometer, *IEEE Trans. Geosci. Remote Sens.*, *1*, 11–17.

Cooley, V. (2013), Unique offerings of the ISS as an Earth observing platform, paper presented at 64th International Astronautical Congress Conference, vol. 8, pp. 1–6, Beijing, China, 23–27 Sept.

Cox, P. M., P. P. Harris, C. Huntingford, R. A. Betts, M. Collins, C. D. Jones, T. E. Jupp, J. A. Marengo, and C. A. Nobre (2008), Increasing risk of Amazonian drought due to decreasing aerosol pollution, *Nature*, *453*(7192), 212–215.

Ehrenberger, W., S. Rüger, R. Fitzke, P. Vollenweider, M. Günthardt-Goerg, T. Kuster, U. Zimmermann, and M. Arend (2012), Concomitant dendrometer and leaf patch pressure probe measurements reveal the effect of microclimate and soil moisture on diurnal stem water and leaf turgor variations in young oak trees, *Funct. Plant Biol.*, *39*(4), 297–305.

European Space Agency (2016), CCI Land Cover Product User Guide version 2.5. ESA CCI LC project.

Friesen, J. (2008), Regional vegetation water effects on satellite soil moisture estimations for West Africa, in *Ecology and Development Series*, Zentrum für Entwicklungsforschung (ZRF), Bonn, Germany.

Friesen, J., S. C. Steele-Dunne, and N. van de Giesen (2012), Diurnal differences in global ERS scatterometer backscatter observations of the land surface, *IEEE Trans. Geosci. Remote Sens.*, *50*(7), 2595–2602.

Frolking, S., T. Milliman, M. Palace, D. Wisser, R. Lammers, and M. Fahnestock (2011), Tropical forest backscatter anomaly evident in SeaWinds scatterometer morning overpass data during 2005 drought in Amazonia, *Remote Sens. Environ.*, *115*(3), 897–907.

Hilker, T., A. I. Lyapustin, C. J. Tucker, F. G. Hall, R. B. Myneni, Y. Wang, J. Bi, Y. M. de Moura, and P. J. Sellers (2014), Vegetation dynamics and rainfall sensitivity of the Amazon, *Proc. Natl. Acad. Sci. U.S.A.*, *111*(45), 16,041–16,046.

Hsiao, T. C., and E. Acevedo (1974), Plant responses to water deficits, water-use efficiency, and drought resistance, *Agric. Meteorol.*, *14*(1–2), 59–84.

Huete, A. R., K. Didan, Y. E. Shimabukuro, P. Ratana, S. R. Saleska, L. R. Hutyra, W. Yang, R. R. Nemani, and R. Myneni (2006), Amazon rainforests green-up with sunlight in dry season, *Geophys. Res. Lett.*, *33*, L06405, doi:10.1029/2005GL025583.

Jaruwatanadilok, S., and B. W. Stiles (2014), Trends and variation in K_u-band backscatter of natural targets on land observed in QuikSCAT data, *IEEE Trans. Geosci. Remote Sens.*, *52*(7), 4383–4390.

Konings, A. G., Y. Yu, L. Xu, Y. Yang, D. S. Schimel, and S. S. Saatchi (2017), Active microwave observations of diurnal and seasonal variations of canopy water content across the humid African tropical forests, *Geophys. Res. Lett.*, *44*, 2290–2299, doi:10.1002/2016GL072388.

Madsen, N. M., and D. G. Long (2016), Calibration and validation of the RapidScat scatterometer using tropical rainforests, *IEEE Trans. Geosci. Remote Sens.*, *54*(5), 2846–2854.

Morton, D. C., J. Nagol, C. C. Carabajal, J. Rosette, M. Palace, B. D. Cook, E. F. Vermote, D. J. Harding, and P. R. North (2014), Amazon forests maintain consistent canopy structure and greenness during the dry season, *Nature*, *506*(7487), 221–224.

Paget, A. C., D. G. Long, and N. M. Madsen (2016), RapidScat diurnal cycles over land, *IEEE Trans. Geosci. Remote Sens.*, *54*(6), 3336–3344.

Perämäki, M., T. Vesala, and E. Nikinmaa (2005), Modeling the dynamics of pressure propagation and diameter variation in tree sapwood, *Tree Physiol.*, *25*(9), 1091–1099.

Phillips, O. L., et al. (2009), Drought sensitivity of the Amazon rainforest, *Science*, *323*(5919), 1344–1347.

Pontes Lopes, A., B. W. Nelson, J. Wu, P. Maurício Lima de Alencastro Graça, J. Valentim Tavares, N. Prohaska, G. Augusto Martins, and S. Saleska (2016), Leaf flush drives dry season green-up of the central Amazon, *Remote Sens. Environ.*, *182*, 90–98.

Saatchi, S. S., R. Houghton, R. Dos Santos Alvala, J. Soares, and Y. Yu (2007), Distribution of aboveground live biomass in the Amazon basin, *Global Change Biol.*, *13*(4), 816–837.

Saatchi, S., S. Asefi-Najafabady, Y. Malhi, L. E. Aragao, L. O. Anderson, R. B. Myneni, and R. Nemani (2013), Persistent effects of a severe drought on Amazonian forest canopy, *Proc. Natl. Acad. Sci. U.S.A.*, *110*(2), 565–570.

Saleska, S. R., K. Didan, A. R. Huete, and H. R. Da Rocha (2007), Amazon forests green-up during 2005 drought, *Science*, *318*(5850), 612–612.

Samanta, A., S. Ganguly, H. Hashimoto, S. Devadiga, E. Vermote, Y. Knyazikhin, R. R. Nemani, and R. B. Myneni (2010), Amazon forests did not green-up during the 2005 drought, *Geophys. Res. Lett.*, *37*, L05401, doi:10.1029/2009GL042154.

Samanta, A., Y. Knyazikhin, L. Xu, R. E. Dickinson, R. Fu, M. H. Costa, S. S. Saatchi, R. R. Nemani, and R. B. Myneni (2012), Seasonal changes in leaf area of amazon forests from leaf flushing and abscission, *J. Geophys. Res.*, *117*, G01015, doi:10.1029/2011JG001818.

Satake, M., and H. Hanado (2004), Diurnal change of amazon rain forest σ_0 observed by K_u-band spaceborne radar, *IEEE Trans. Geosci. Remote Sens.*, *42*(6), 1127–1134.

Sevanto, S., T. Vesala, M. Perämäki, and E. Nikinmaa (2002), Time lags for xylem and stem diameter variations in a Scots pine tree, *Plant Cell Environ.*, *25*(8), 1071–1077.

Sevanto, S., E. Nikinmaa, A. Riikonen, M. Daley, J. C. Pettijohn, T. N. Mikkelsen, N. Phillips, and N. M. Holbrook (2008), Linking xylem diameter variations with sap flow measurements, *Plant Soil*, *305*(1–2), 77–90.

Sevanto, S., T. Hölttä, and N. M. Holbrook (2011), Effects of the hydraulic coupling between xylem and phloem on diurnal phloem diameter variation, *Plant Cell Environ.*, *34*(4), 690–703.

Slayter, R. (1967), *Plant-Water Relationships*, Springer, Dordrecht, Netherlands.

Steele-Dunne, S. C., J. Friesen, and N. Van de Giesen (2012), Using diurnal variation in backscatter to detect vegetation water stress, *IEEE Trans. Geosci. Remote Sens.*, *50*(7), 2816–2629.

Tardieu, F., and W. Davies (1993), "Integration of hydraulic and chemical signalling in the control of stomatal conductance and water status of droughted plants,"*Plant Cell Environ.*, *16*(4), 341–349.

Ulaby, F. T., A. Aslam, and M. C. Dobson (1982), Effects of vegetation cover on the radar sensitivity to soil moisture, *IEEE Trans. Geosci. Remote Sens.*, *4*, 476–481.

Ulaby, F., C. Allen, G. Eger, and E. Kanemasu (1984), Relating the microwave backscattering coefficient to leaf area index, *Remote Sens. Environ.*, *14*(1–3), 113–133.

van Emmerik, T., S. C. Steele-Dunne, J. Judge, and N. van de Giesen (2015a), Impact of diurnal variation in vegetation water content on radar backscatter from maize during water stress, *IEEE Trans. Geosci. Remote Sens.*, *53*(7), 3855–3869.

van Emmerik, T., S. Steele-Dunne, J. Judge, and N. van de Giesen (2015b), A comparison between leaf dielectric properties of stressed and unstressed tomato plants. paper presented at 2015 IEEE International Geoscience and Remote Sensing Symposium (IGARSS), pp. 275–278, IEEE, Milan, Italy, 26–31 July.

van Emmerik, T., S. C. Steele-Dunne, J. Judge, and N. Van De Giesen (2017a), Dielectric response of corn leaves to water stress, *IEEE Geosci. Remote Sens. Lett.*, *14*(1), 8–12.

van Emmerik, T., S. C. Steele-Dunne, R. Hut, P. Gentine, M. Guerin, R. S. Oliveira, J. Wagner, J. Selker, and N. van de Giesen (2017b), Measuring tree properties and responses using low-cost accelerometers, *Sensors*, *17*(5), 1098.

Zweifel, R., and R. Häsler (2001), Link between diurnal stem radius changes and tree water relations, *Tree Physiol.*, *21*(12–13), 869–877.

Zweifel, R., L. Zimmermann, and D. Newbery (2005), Modeling tree water deficit from microclimate: An approach to quantifying drought stress, *Tree Physiol.*, *25*(2), 147–156.